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# MSM-Metal Semiconductor Metal Photo-detector Using Black Silicon Germanium (SiGe) for Extended Wavelength Near Infrared Detection

**by Fred Semendy, Patrick Taylor, Gregory Meissner, and Priyalal Wijewarnasuriya**

**ARL-TR-6176** **September 2012**

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**14. ABSTRACT**

We have investigated for the first time the electrical properties of metal-semiconductor-metal (MSM) photodectors fabricated using black silicon-germanium on silicon substrate ($Si_{1-x}Ge_x$/Si) for I-V, optical response, external quantum efficiency (EQE), internal quantum efficiency (IQE), and responsivity and reflectivity. Silicon-germanium ($Si_{1-x}Ge_x$)/Si with variations of Ge were blackened by metal enhanced chemical etching (MECE) using nanometer-scale gold particles as catalyst and $HF:H_2O_2:CH_3COOH$ solution as etchant. The etched surface was black, textured, and showed strong suppression of reflectivity. These properties are consistent with $Si_{1-x}Ge_x$ becoming highly micro-structured due to metal catalysis and wet etching. Using the blackened SiGe/Si, MSM photodiodes were fabricated and tested. The lowering of reflection using a U.S. Army Research Laboratory (ARL)-developed technique has helped the enhancement of absorption in $Si_{1-x}Ge_x$ to provide increased optical response, which is an important milestone towards practical, extended wavelength (~2 μm) electro-optical applications.

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# 1. Introduction

The growth of high quality nano-scaled silicon germanium (SiGe/Si) layers and Ge islands on Si substrates by ultra high vacuum/chemical vapor deposition (UHV/CVD) has attracted intense interest because of the prospect of band gap engineering (*1*). For large scale infrared (IR) detector systems, SiGe/Si is a favorable material system because of perfect thermal matching to the Si readout circuit and adaptable peak and cut-off wavelength. Some of the important applications of SiGe/Si are satellite imaging and observation, heat sensing, medical diagnostics, and missile tracking. The Army would like to use the SiGe/Si material system as a replacement for an expensive InGaAs detection and imaging system. To make SiGe/Si comparable in efficiency, the reflective property of the material must be reduced and the absorption property has to be increased by using one of the available techniques.

Over the past 10 years, new phenomena based on nanostructuring the surface of Si have been investigated for application to infrared imaging. In 2003, Mazur and colleagues reported that using femtosecond laser processing coupled with halogenated etching gas could produce silicon surfaces having sub-micrometer corrugated conical tip microstructures (*1*). These microstructures had the special property such that the surface of the silicon was rendered almost perfectly non-reflective. They named this material "black silicon." In that early study, they showed that when they produced that microstructure using only halogenated etching gas (sulfur hexafluoride [$SF_6$]), the spectral absorbance of light was extended well beyond that which would be expected from the conventional band-theory understanding of silicon. In subsequent reports from researchers in the Mazur group, evidence began to point to the very highly doped surface region (sulfur-doped) on the etched surface that seemed to promote sub-bandgap absorption (*2*). In that work, they demonstrated this important result: after forming the etched surface, the extended wavelength infrared absorbance could be decreased and almost completely eliminated because of dopant evaporation during high-temperature annealing. Based on these early results, the Mazur Group partnered with device researchers at the University of Virginia and the University of Texas at Austin to demonstrate a novel infrared detector based on this new material (*3*).

The researchers in this partnership showed two very important demonstrations: (1) the spectral responsivity was enhanced compared to that of conventional silicon photodetectors, and (2) responsivity was extended to longer infrared wavelengths (1.3 and 1.55 μm), beyond the spectral range generally expected from silicon, which is limited to about 1.1 μm. While there is some uncertainty about the mechanism that enables sub-bandgap, longer wavelength detection, the mechanism is currently explained as longer wavelength photons excite carriers across the energy difference between mid-gap defect states from the heavily doped region and the

conduction band edge. While the science behind the phenomena is being resolved, these interesting results presage new, low-cost near-infrared detectors that could have important military and civilian applications. However, for tactical military applications, a much higher spectral response at extended wavelengths in the near-infrared (~2 μm) would be desired. To that end, we are investigating $Si_{1-x}Ge_x$ materials with the goal of obtaining an improved photo response out to 2 μm by (1) shrinking the bandgap so that the *difference between the conduction band-edge and the defect state is reduced* and (2) providing a naturally larger absorption coefficient for longer wavelength light. So this work builds upon the results reported from the Mazur and partner groups, and investigates new heavily doped black $Si_{1-x}Ge_x$ materials. Some important differences between this work and the approach of the Mazur and partner groups are (1) we employ a metal-masked, wet-chemical etching approach versus a femtosecond gas-phase etching process, and (2) we used in-situ boron doping $p \approx 5x10^{19}/cm^3$ versus sulfur doping $n \approx 5x10^{20}/cm^3$ from the past work.

Our investigation with black $Si_{1-x}Ge_x$ is very important since SiGe is a good substitute material for Si for many applications in low-power and high-speed semiconductor device technologies (*4, 5*). It is a promising material for quantum well devices (*6*), infrared detectors (*7*), and modulation doped field-effect transistors (MODFET) (*8, 9*). Recently, much work has been planned to use $Si_{1-x}Ge_x$ for optodetectors and micro-electro-mechanical systems (MEMS) sensors and actuators. Activity is also being continued to develop flip chip optical receives. Among the many other applications currently being considered are strained SiGe on silicon to be used as base in a heterojunction bipolar transistor (HBT) in a bipolar complementary metal oxide semiconductor (BiCMOS) process and complementary metal oxide semiconductor (CMOS) logic applications. SiGe has much to offer for the fabrication of devices with improved efficiency (*10*). In a particular instance, self-assembled Ge-islands and black Ge based on nano-needle arrays have been developed (*11*). Increased absorption of light is essential to create highly efficient opto-sensors and photovoltaic devices. To achieve this, efficient three-dimensional (3-D) structures with relevant material systems are required. Apart from these two techniques, others (*12, 13*) have proposed a technique in which multicrystalline SiGe bulk crystal with microscopic compositional distribution is grown using the casting technique. The average Ge composition was changed systematically between 0% and 10%. A small addition of Ge to multicrystalline Si was found to be very effective to increase the short-circuit current density without affecting open circuit voltage. They also indicated that such grown SiGe materials are promising candidates for solar cell and other opto-electronic applications. For such applications, SiGe has to be prepared with reduced reflectivity and increased absorbance. This can be achieved through surface texturing, as has been used in the case of black silicon. In general, for a 3-D blackened surface, reactive ion etching or wet anisotropic etching are the techniques of choice. Although reactive ion etching can provide a structure with a high aspect ratio, it involves rather complicated procedures. Metal enhanced chemical etching (MECE) (*14, 15*), by which silicon is etched using

metal thin films or particle as catalysts, is an attractive procedure because it is simple and easier to perform with good results.

SiGe/Si heterostructures are expected to play a major role in Si-based optoelectronics (*16, 17*). Recent advances in SiGe heteroepitaxy techniques for the growth of strained $Si_{1-x}Ge_x$ layers have extended their applications in Si-optoelectronics. The importance of Si/SiGe strained layers lies in the possibility of integrating optoelctronic devices. Due to the compressive strain in SiGe alloy films, the bandgap of $Si_{1-x}Ge_x$ alloys can be tailored continuously from Si (x=0, 1.17eV) to Ge (for x=1, 0.66 eV) at room temperature (*18*). Si is transparent in the 1.3–1.6 µm wavelength range, and the SiGe absorption edge shifts towards the red with increasing Ge fraction. The shift offers a means absorbing 1.3–1.6 µm light, if desired by choosing x > 0.3 for 1.3 µm light and x > 0.85 µm for 1.55 µm.

## 2. Experimental Details

The $Si_{(x)}Ge_{(1-x)}$ alloy layers in this work were grown on 8-in silicon substrates having either (111) or (100) orientation and etched as described in (*19*). Etched $Si_{1-x}Ge_x$/Si with varying Ge concentration was used for the fabrication of the metal semiconductor metal (MSM) photodetector. Standard processing techniques were used. After defining the pattern on the top surface, Schottky metal contacts were made on the surface of the absorption layer. Here the device is in contrast to the normal Schottky photodiode that has top and bottom metal contacts. The MSM pattern has two back-to-back diodes in series—one forward-biased and the other reverse-biased. In the dark condition, there is only a little reverse saturation current produced in the biased photodetector, which is called the dark current of the device. Figure 1 depicts the structure of the MSM.

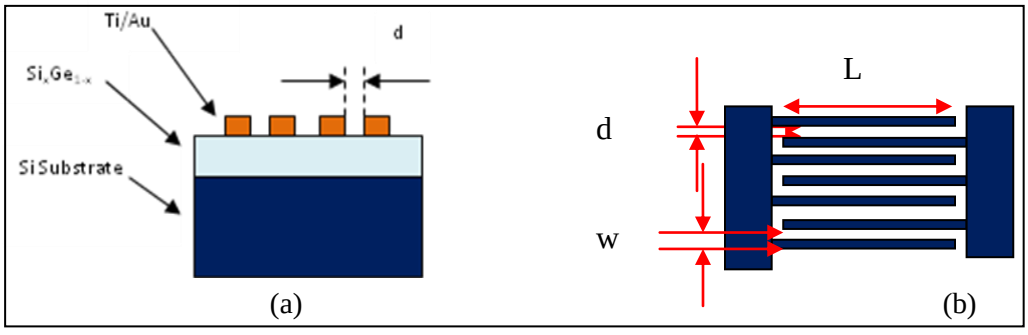


Figure 1. Basic structure of MSM photo detector (a) $Si_{1-x}Ge_x$/Si material and (b) MSM device.

When light is shone onto the surface of the device, it will be absorbed within the underlying semiconductor at a depth depending upon the wavelength and the absorption coefficient of the

material. It is worth mentioning here that we have modified the semiconductor surface with the intention of increasing the absorption, thus increasing the quantum efficiency and responsivity. The absorbed light will produce electron-hole pairs, and with an application of a bias to the metal fingers, an electric field will be created within the underlying semiconductor that sweeps the photo-generated carrier out of the depletion region resulting in a photocurrent. The collection efficiency of the MSM will depend upon the magnitude of the applied voltage and finger separation (d). The metal fingers are fabricated with Ti/Au (200 nm/2500 nm). Fabricated devices were used for I-V measurements using Agilant 4160 Parametric Analyzer to obtain the dark current, as well as optical response under varying optical power. A broadband source was used for the input light.

We used the Oriel IQE-200 EQE/IQE measurement for extended wavelength range to measure the QE. The IQE 200 incorporates a novel geometry that splits the beam, allowing for simultaneous measurement of EQE (external quantum efficiency) and the reflective losses to quantify IQE (internal quantum efficiency). The power spectral responsivity $R_{pa}(\lambda)$ for collected electrons per incident photons may be converted to external quantum efficiency QE (λ), and then to IQE (λ), using the equations,

$$QE\ (\lambda) = \frac{hc}{q}\frac{Rpa(\lambda)}{\lambda} \tag{1}$$

$$IQE\ (\lambda) = \frac{QE\ (\lambda)}{1 - Rsample\ (\lambda)}, \tag{2}$$

where $Rsample\ (\lambda)$ is effective sample reflectance.

The optical layout of the beam splitter in the IQE 200 system is illustrated in figure 2. It is comprised of one spectrally neutral 50-50 beam splitter and four lenses. The output light from the monochromator is first collimated by lens 1. The collimated light is then split into two beams of which one passes through the beam splitter and is focused by lens 2 onto the Reference Detector. This detector measures the output light of any given wavelength. The other beam is reflected by the beam splitter down onto the sample surface through focusing lens 3 for the QE measurement. The spot size on the sample is determined by the lens 3. Therefore, by varying the lens 3 optical parameters, a variety of spot size options can be obtained. For the internal quantum efficiency measurement, the reflected light from the sample is collimated lens 3 and then a known factor of it passes through the beam splitter. The beam is then focused by lens 4 on to the reflectance detector (figure 3).

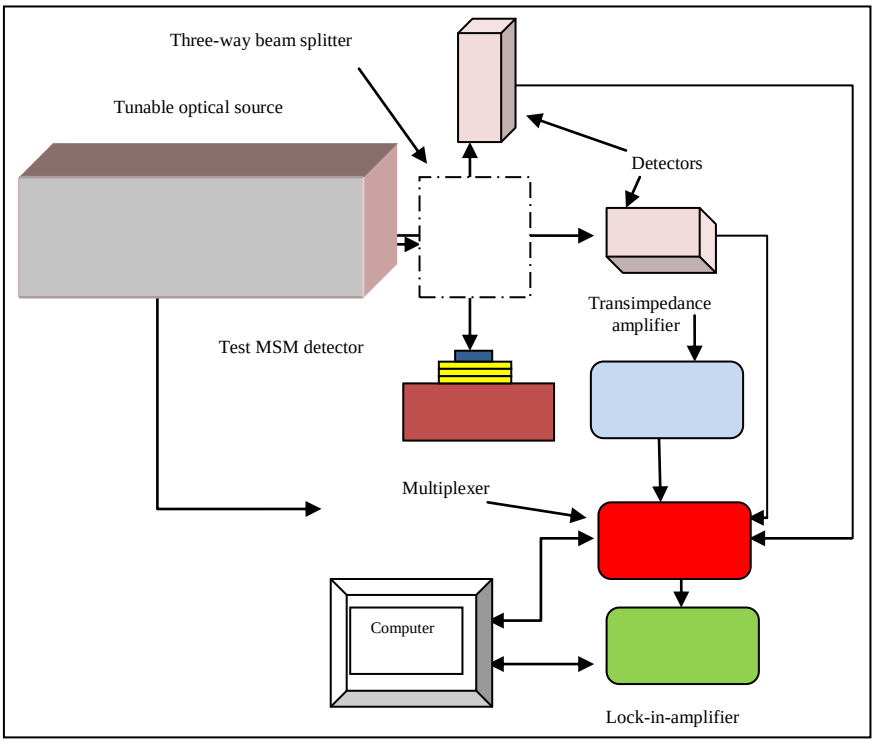


Figure 2. Block diagram of IQE 200 EQE/IQE measurement system.

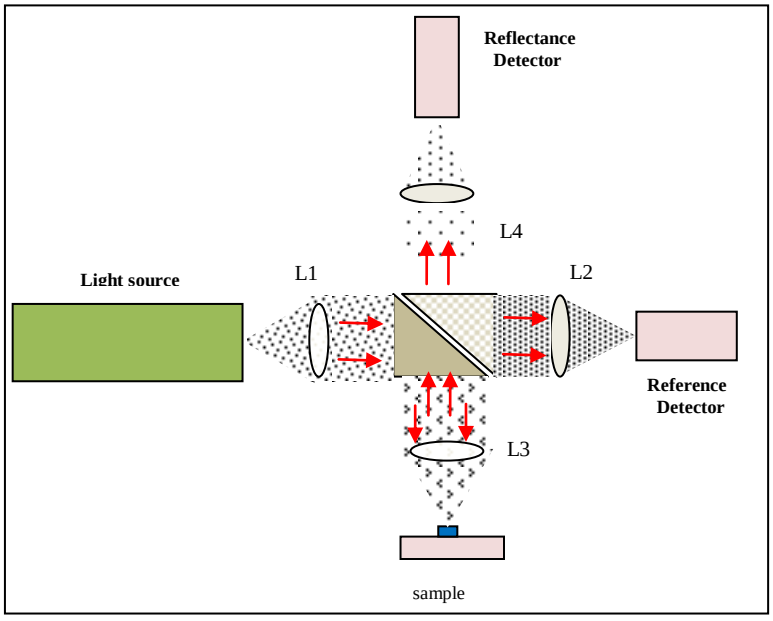


Figure 3. Depiction of the beam splitter and its effect on the optical beam.

## 3. Result and Discussion

Figures 4a and b give the current-voltage curves of the $Si_{1-x}Ge_x/Si$ MSM detectors, with 15% and 30% Ge-containing samples. The optical illumination was provided by 5 and 10 mW white light sources.

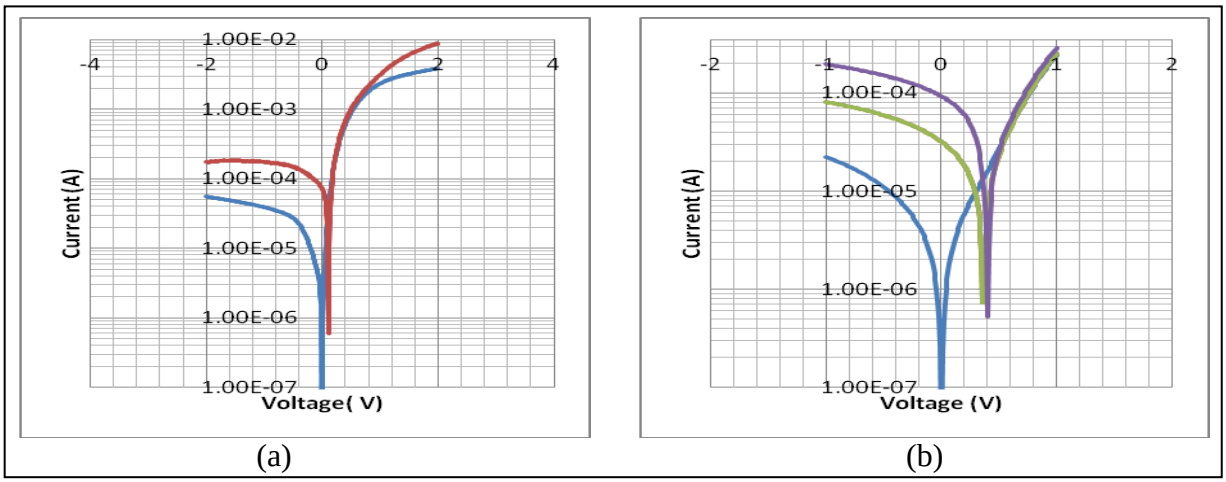


Figure 4. I-V curves for $Si_{1-x}Ge_x/Si$ MSM photodiodes. (a) 15% Ge with and without 5 mW light (red) and (b) 30% Ge MSM device with 5 (green) and 10 mW lights (Lavender).

The clear dependence of the response on the optical power of the illumination source is evident here. The dependence is increased with respect to the amount of Ge in the semiconductor surface.

Figure 5 gives the I-V curves of $Si_{1-x}Ge_x/Si$ with 15% but etched for (a) 5 min and (b) 10 min, followed by the fabrication of MSM detectors. Comparing the results, one can see that there is increased optical response for two similar samples containing the same amount of Ge but with the surface etched for varying times. Clearly, one can observe the enhanced optical response due to greater absorbance of photons on the second sample.

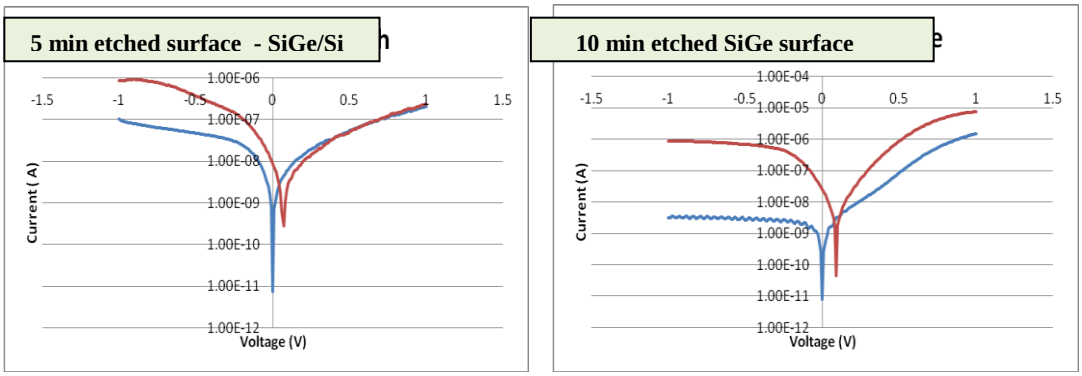


Figure 5. I-V curves for $Si_{1-x}Ge_x$/Si MSM photodiodes. (a) 5 min etched 15% Ge with 5 mW light(red) and (b) 15% Ge MSM device with 10 min etch 5 mW illumination.

The effect of optical filtering on the optical response was studied in another set of samples, since $Si_{1-x}Ge_x$/Si is expected to show detection ~1600 nm. However, we wanted to see the effect of using a GaAs wafer and a Si wafer as filters. For a particular optical power, current measurements were obtained first for a GaAs filter and then Si filter. In another case for a particular optical power of optical illumination, the time response was recorded for varying voltages. These two cases are shown in figures 6a and b.

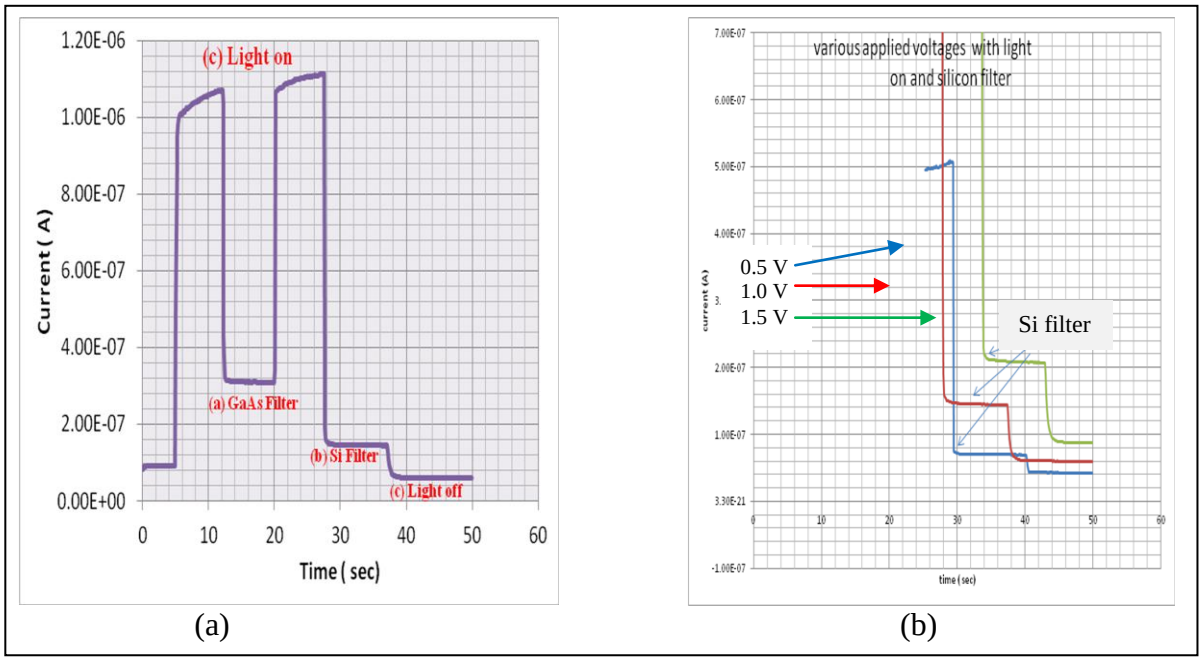


Figure 6. Time based optical response of $Si_{1-x}Ge_x$/Si MSM detector. (a) response with a GaAs filter, and a Si filter. (b) with Si filter and varying applied voltage, 0.5 V, 1.0 V, and 1.5 V.

Using GaAs filter has shown the effect of filtered optical beam beyond 960 nm, and the amplitude of the response current has dropped substantially to about 70% of the unfiltered. Next, using the Si filter has drastically cut down the power to 90%, yet still showing response.

Further, it is shown that as the applied voltage increases the collection efficiency, the response current also increases, as seen in figure 6b.

Measurement of the optical reflectance and further calculation of QE, IQE, and responsivity were carried out using equations 1 and 2 for a MSM detector made up of a $Si_{0.85}Ge_{0.15}$/Si, which was wet-etched for 10 min, as indicated earlier. The reflectance, QE (λ), and spectral responsivity of a 15% Ge-containing $Si_{0.85}Ge_{0.15}$/Si, which was wet-etched for 10 min prior to the fabrication of the MSM detector, are plotted with respect to the wavelength and shown in figure 7. The measurements were taken without any applied voltage at zero bias.

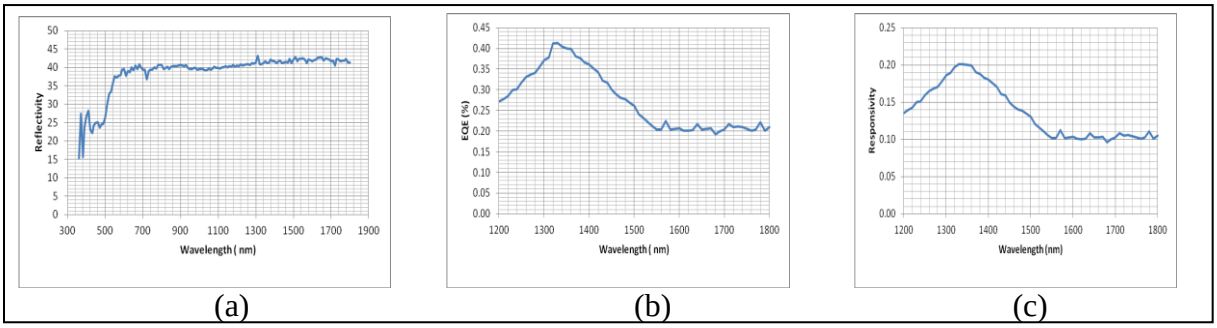


Figure 7. (a) Reflectance of the sample $Si_{0.85}Ge_{0.15}$/Si etched for 10 min, (b) QE ( λ), and (c) spectral responsivity of the same sample with zero bias.

These results obtained in our experiments are similar to or even better than some of the other work for a zero bias applied voltage (*20*).

## 4. Conclusion

We fabricated MSM detectors using wet-etched SiGe/Si samples with varying amounts of Ge, and studied their electrical properties of I-V, optical response, QE, and responsivity under zero bias and the results reported. We observed increased response current as the amount of Ge increased in the sample. Similarly, we observed enhanced response current as we changed the etching time of the sample indicative of increased absorption. The significance of this work is that for the first time, infrared detection beyond the band edges of both silicon and gallium arsenide is shown to be feasible with black-SiGe. Although the response is low, this is due, for the most part, to the small initial thickness of the SiGe layer. Because the absorption coefficients of Si, Ge, and SiGe are much smaller than that of, say, InGaAs, much larger thicknesses are required to obtain the same absorbance. The SiGe layers of this work are less than one micron; so clearly, for future work, thicker layers will provide dramatically better response than that shown here. However, the key point from this work is that there is a clear path toward very-low cost infrared sensing technology that employs blackened SiGe.

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